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The Research and Development Program at the National Meteorological Center

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PREFACE

This is frankly in the nature of a white paper, with almost total emphasis on successes and work in numerical weather prediction and related activities at the National Meteorological Center. Little apology is required, since the direct source of advances in the Center's guidance material has been almost exclusively the in-house research and development program of the Center. Researchers at the Center, however, work within a national and international community of academic and research scientists concerned with atmospheric modeling, which provides a source of ideas for research as well as a stimulus for new ideas.

The paper covers 18 years of advances in operational numerical weather prediction. There have been a myriad of innovations during that period, far too many to discuss here. Only high-lights are therefore covered, and those only briefly.

I. Introduction

When the Joint Numerical Weather Prediction Unit *(JNWPU) was organized in July 1954, there were two ways that it could have gone. One way was to study the mechanics of the atmosphere, to look for tools to be used by the forecasters, and at the same time to develop and ultimately to demonstrate the utility of Numerical Weather Prediction (NWP) as an operational product in itself. The second way was to proceed immediately to operational NWP production.

The Joint Meteorology Group *(JMG) at the beginning directed JNWPU to pursue the latter course. In large part, as it turned out, this was based on false optimism about the short term, but in the long term this decision by JMG was crucial to the success of the effort.

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* The Joint Numerical Weather Prediction Unit was organized in 1954 within the National Weather Service, but was supported equally with personnel and funds from the National Weather Service, the Air Weather Service (USAF), and the Naval Weather Service (USN). It was steered by the Joint Meteorology Group, an inter-agency committee consisting of the heads of the three weather services. In July 1961 NMC was formed within the National Weather Service, with entirely their support. JNWPU, along with the National Weather Analysis Center and Extended Forecast Branch, formed the NMC, with organizational lines drawn as at present.

Models to be considered for operations at the time were Charney's Princeton three-level model [1] and Thompson and Gates' two-level thermotropic model [2]. The former had been run on 14 cases, the latter on 60, and based on the results it had been assumed that either would serve well operationally. The question at the time seemed to be one of choice between the two. Since the testing and evaluation had been done independently from each other, and not on the same cases, much comparability was lacking, and the choice was not a straightforward one.

The decision was in favor of the Princeton three-level model. What later ensued was a retrogression backward from the three-level to the two-level and finally to the single-level barotropic model [3]. When the three-level model was programmed for the IBM-701 in 1955, run on an operational schedule, and subjected to the critical eye of the practicing synoptician in real time, it was discovered to be unable to predict reliably and accurately.

Although disappointing at the time, in retrospect this was an experience which was the key to future success, and was the immediate and essential result of the decision by JMG to "go operational." This baptism by fire immediately brought to bear the combined talents of the modeller, the judgment of the practicing synoptician, and the skills of the computer programmer. It established patterns of motivation with attention centered on accuracy and timeliness of delivery. This concentration of effort was a product of the operational environment.

II. The Barotropic Model

More than back-breaking labor, as it has been described, was required to achieve operational NWP. Fundamental essential discoveries in mathematics and the physics of the atmospheric fluid were first to be made.

The three-level model was soon abandoned in favor of the two-level, which for similar reasons was abandoned in turn in favor of the single-level barotropic model. The barotropic model, too, was found to be lacking in essential skill, but in its relative simplicity it set for the researcher a tractable problem. This in itself was a pattern often repeated later, the moral being, when confronted with a problem try to capture it in the simplest possible system.

Three things were wrong with the barotropic, two of which called for fundamental research. These same things were also wrong with the two- and three-level models, but in their complexity they had additional errors.

It is well to say here that the bulk of the theory of all of these models was basically sound, and their framework was later proven in operation. It is fair to describe the situation, not as a case of faulty theory, but rather as a case of incomplete theory. In light of the pre-judgment of the models' operational suitability, the operational environment must be considered as a necessary milieu for completion of the theory. Through repetition during 15 years this is now a well established principle.

The symptoms of the two fundamental things wrong with the early barotropic model were excessive retrogression of the planetary-scale waves and spurious anticyclogenesis in low middle latitudes. The former was due to lack of an adjustment mechanism between mass and motion and was solved with the so-called Helmholtz term in the barotropic equation [4]. The latter was due to divergence of the geostrophic wind which was explicitly used in the early barotropic model. It was solved through use of a stream function derived from the balance equation [5]. Operational use of the balance equation itself depended on successful fundamental mathematical research [6].

The third thing wrong with the barotropic model was its restricted area of integration, although probably only for periods beyond 24 hr. This was solved by enlarging the area of integration virtually to cover the Northern Hemisphere. Acquisition of the more powerful IBM 704 was essential for this purpose.

With this research completed, the first successful operational barotropic model was inaugurated. Operational success, however, did not depend only on NWP research advances but also on coincident advances in technology. As the first numerical predictions were not reliably accurate, so were they not timely. Automatic processing of the incoming data, numerical weather analysis, and automatic graphical output had to be developed.

The first operation in 1955 depended on hand methods of analysis and primitive communications methods. The collection and preparation of data, punching of cards, and manual checking of the input required about

10 hours from the nominal data time which meant that products were not available for use until 12 hours after the nominal data time. Early in the first operation a form of machine graphical output was developed for a line printer. Even on today's machines it has survived as an economical quick method of output. Experiments were made with machine methods of input data processing and machine analysis, but the problems of error control, running time, and costs were not adequately solved on the first machine. This had to wait for the more powerful IBM 704.

The first analysis method used was a sectionalized fit of second-degree polynomials [7]. Because the method had difficulties with uneven data distribution such as around silent areas, and was expensive in machine time, it was abandoned in favor of a scheme invented by two Swedes, Bergthorsen and Doos [8]. Their method was revised at NMC [9] to accumulate the results of all of the corrections at a grid point. Considerable effort was made to protect the analysis against gross errors and early efforts were directed to allow manual modification of the result, particularly over oceans and other sparse data areas. Early in this development the benefits of adjustment of the previous forecast by new data were shown and the concept of a forecast-analysis cycle came into being.

Parallel developments for input of data occurred. A start was made with hand punching of data cards and was followed by automatic paper-tape-to-card conversion. This introduced a new concept called ADP (automatic data processing) before that term began to have a wider meaning in computer science. It concerns itself with reading of remotely manually prepared teletype texts into computer-quality data bases. It has many of the qualities of reading natural languages, although the forms are fortunately more restricted. The input text contains observations in a dozen or so formats, with variations and errors normally found in language, that must be recognized in context amid extraneous material. Development of the method, together with the introduction of high-speed paper-tape readers on the IBM 1401, enabled an advance from a start 10 hours after data time in 1955 to a start 6 hours after data time in 1959. In addition, the number of fields and levels analyzed have increased.

The advances so far described enabled the first numerical weather prediction operation which successfully exceeded the minimum requirements of quality and timeliness. The result on quality of central guidance can clearly be seen in Figure 1 as the drop in S1 score in 1958.

III. Baroclinic Models

The barotropic model takes no account of conversion of potential and internal energy to kinetic energy and therefore does not predict development of storms. This was the next big problem to be tackled. Initial success was achieved with the NMC three-level filtered-equation model [10]. It not only utilized the theory and structure of the Princeton three-level model [1] along with the new "corrections" contained in the barotropic model, but also used theoretically derived factors essential for filtered baroclinic models. The principal departures of the NMC three-level model from its predecessors were an additional term for advection of vorticity by the divergent component of the wind, use of the balance equation to maintain the proper relation of the mass field to the wind field during the integration, and the careful construction of finite-difference forms and numerical procedures to prevent systematic accumulation of truncation error.

This first successful baroclinic model became operational in 1962. Acquisition of the more powerful IBM 7090 was an essential enabling factor. The three-level model established a new lower plateau of error not clearly seen in Figure 1 because of the rise in 1964-6. The rise was also exhibited in barotropic scores, so it may safely be concluded that it was due to weather unusually difficult to forecast. In spite of the anomalous rise, S1 scores during the three-level era were lower than the barotropic era.

A development, unique at the time, occurred at NMC in the mechanical curve-plotter. Curve-plotters had existed before but the transistorized models that appeared in 1958 were the first whose plotting speed could meet weather requirements. NMC took advantage of the state-of-the-art and developed algorithms for finding contours, following contours with acceptable accuracy, locating centers, and drawing a production map able to meet critical standards. These were developed by 1959 in conjunction with the speed-up of the National Facsimile Circuit to 120 RPM. Expansion occurred rapidly with the addition of facsimile circuits until today 500 charts are prepared for facsimile transmission.

Research with the primitive equations was begun in 1959. The overwhelming problem at the time was an accumulation of truncation error early in the integration, intimately connected with the non-linearity of the equations, and usually referred to as "non-linear instability" to distinguish it from the problem which Courant, Friedrichs, and Lewy [11] analyzed. Experiments with numerical systems borrowed from others' work quickly proved that no acceptable numerical system existed. No theory existed for stability of non-linear systems, and even today theory is only rudimentary, although perhaps the most complete theory existing today in this area was developed in 1969 by NMC workers in collaboration with the Canadian, Robert [12], and was built on earlier work by N. Phillips [13] and Richtmyer [14].

The approach taken to the problem was cut-and-try. The first problem in designing the research project was to select a workable number of difference systems with which to experiment, for without guiding theory the possible number of forms is virtually infinite. The second problem was to capture the instability in the simplest possible physical system, so that large numbers of cut-and-try experiments could be run in a reasonable time. Forms passing tests with very simple physical systems were subjected to tests with more complex physical systems, and so on up the hierarchy of complexity to a full-scale primitive-equation NWP model. By mid-1961 two acceptable forms had been discovered, one of which is still used operationally [15]. It was not until the 1969 work that the relative stability of the two forms was at least partly explained [12].

From the standpoint of know-how, NMC could have launched a primitive-equation operation in 1961. The primitive-equation model, however, requires far more calculations than do filtered-equation models, and its lack of timeliness delayed a primitive-equation operation until mid-1966 [16]. Enabling factors in that year were acquisition by NOAA of the more powerful CDC 6600, and the appearance of the U.S. Air Force Automated Weather Network (AWN). The AWN provided faster data collection, and allowed an earlier start of the operation.

The effect on guidance quality of the introduction of the NMC six-layer primitive-equation model can clearly be seen in Figure 1 by the drop, beginning in 1966, of S1 at 500 mb.

The behavior of the various models at 500 mb is an important indicator of general skill of models, and because of the high auto-correlation in the vertical of winds from 700 mb well into the stratosphere, it is almost a direct indication of skill in forecasting winds for aviation. Most of the forecast service, however, is directed to conditions at the surface of the earth. For this the quality of central guidance at sea level (or the earth's surface) is perhaps NMC's most important product. Figure 1 shows that NMC's sea-level pressure prognoses have experienced a remarkable decline in error as measured by S1, beginning with introduction of timely and accurate barotropic models in 1958.

The S1 record shown for sea level in Figure 1 is for manually prepared prognostic charts. The decline of S1 between 1958 and 1962 is due entirely to the human analysts' ability to learn to use information from more accurate predictions in mid-atmosphere in the preparation of sea-level prognoses.

The first useful numerical prediction at sea level was achieved by Reed [17] during a year's visit to NMC. It went into operation in 1962. In framework, it drew from the early two-level thermotropic models, using 500 mb predictions made independently by the operational models already discussed. Although it could not compete directly with manual prognoses, not even those made prior to 1958, it did provide the analyst with much useful information about the development and placement of sea level systems. The continuing decline of S1 at sea level between 1962 and 1966 is largely attributed to Reed's model.

The NMC six-layer primitive equation model [16] was the first to produce a sea-level predictiondirectly competitive with the manual predictions. By itself, in fact, the model produces a more skillful forecast than the man can produce without NWP guidance. For instance, the "raw" sea-level NWP in 1971 averaged only five S1 points higher than the score for the manual product shown, still well below the scores prior to 1958. The five S1 points the man contributes are an important five points, however. They can be translated into five years of progress. Without the analysts' skill, the product would now be only at the 1966-7 level of skill. The analyst contributes other essential skills to NMC's products, especially in quantitative precipitation and cloudiness forecasting and in frontal analysis. Man's part in the man-machine mix is essential to overall quality, and will remain so for the foreseeable future.

The six-layer primitive equation model has been under continuous development since 1966. At its inception, by the way, the model had the effects of skin friction, transfer of heat from warm oceans, and topographical effects. A few of the more major subsequent improvements have been introduction of a water-vapor and latent-heat calculation beginning with one level of resolution [18] (precipitable water) and later with three levels of resolution [19], introduction of both long- and short-wave radiation effects [20], improvement of the description of topography to as accurate a representation as the grid can carry [21], and introduction of the effects of convective rain [22]. The reduction of pressure to sea level was also improved in the output, in 1970 [23].

The use of the balance equation in relating initial winds for the model to the mass field was discontinued last year. Direct wind analyses are now used instead [24]. Much work on the initialization problem had been done at NMC by Nitta and Hovermale [25] and by Okland [26]. These efforts, like most work elsewhere, used the dynamics of the model itself to obtain the initial relationship between mass and motion. None of these have worked well in tests, and use of direct wind analyses may well be the long-term solution.

In 1971 the local area fine-mesh model (LFM) [27] was introduced into operation. In its essentials it is the same as the NMC six-layer primitive equation model, but with half the mesh size and time-step, and a quarter of the area. It covers roughly an octant of the globe.

A major new problem which had to be solved for operational feasibility of the LFM was handling of the lateral boundary, which cuts across meteorologically very active areas (jet streams, etc.). In its current version, boundary values are held constant, and energey-absorbing devices are employed near the boundary to control the integration. This in itself is an important departure from the work of others, who generally take boundary values from large-scale models like NMC's six-layer primitive equation model. Operational requirements provide strong reasons not to link the LFM with the hemispheric model. The LFM is directed to shorter period forecasts (it is only run to 24 hr), and for operational reasons, therefore, should be run before the hemispheric model, as is done at NMC.

The LFM has been operational for only a few months, too short a period to accumulate reliable verification statistics. It so far shows promise, especially in translation of relatively small-scale systems, development of storms at sea level, and in quantitative precipitation forecasting.

IV. Related Development and Continuing Research

Tropical areas differ in fundamental ways from middle and high latitudes, from the standpoint of both analysis and prediction. Much of what has been learned about the extratropical regions cannot be applied to the tropics. In the case of analysis, important pressure variations in the Tropics are below the noise level of measurement. The principal parameter to be analyzed is therefore the wind. The analysis system [28] developed at NMC for the Tropics in 1966 is on a 5°-mesh covering the entire tropical belt from 48N to 48S. Both the u and v components of the wind are directly analyzed, and in such a way that a stream function accurately represents the vector wind field. At the time of its development, this system was a unique achievement.

As yet there is no known way to accurately predict the tropics numerically, with the exception of the occasional but important well developed tropical storms. For NMC's aviation wind and temperature forecasts, which cover the globe wherever there are commercial flights, persistence is used in the tropics and the tropical analyses provide the persistent values.

Continuous improvement in other analysis techniques have been made at NMC. Non-geostrophic use of the wind in height analysis was started in 1965 [29]. Development of a satisfactory tropopause analysis [30] began in 1964, and is essential input to the NMC six-layer primitive equation model. Vector wind analysis was started in 1960, before it was extended to a tropical subarea in 1962 in Honolulu [31], and later at NMC to the global equatorial strip in 1966 [28].

Much current work in NMC is directed toward completely automated graphics. Following the curve plotters, an attempt was made to introduce a microfilm operation. An unfortunate experience in this direction followed with a prototype machine, whose resolution was never good enough for facsimile practice. Then a decision was made to go to a completely automatic system wherein the map, including lines, labeling, and plotting, is generated as a numerical product. This product is now distributed by a computer directly into the facsimile circuits. The present system drives three facsimile circuits and is being upgraded to eight circuits, some of them at 240 RPM. This now accounts for 60 per cent of the total facsimile program. Of the remainder, 30 per cent is satellite pictures (also highly automated) and 10 per cent is manually produced.

The extended forecast (three to five days) program at NMC benefited from NWP research at NMC as well as did the shorter range forecasts. Numerical guidance to six days has been used by the extended forecaster since before the turn of the 1960's. Generally, these have been barotropic extensions of the 36 and 48 hr operational runs. Beginning in early 1970, the program was increased from a thrice weekly to a daily program. This was enabled by a once daily extension of the operational model to 84 hr and a further barotropic extension to 6 days. The additional material provided by the operational model, as well as supplementary statistical objective tools developed in the research program of the Extended Forecast Division, enabled the increased program with a simultaneous reduction in staff. The savings in salaries paid for the additional computer costs.

Another important research program is conducted by Upper Air Branch, which concentrates on analyses from 100 to 0.4 mb [32] [33]. They provide the leading U.S. expertise in use of rocketsonde meteorological data [34], have been instrumental in the SIRS retrieval problem [35], and they operationally issue stratospheric warming forecasts [36]. They are perhaps most widely known for their work in analyzing errors in various radiosonde instruments at very high altitudes [37].

Air Pollution Potential guidance predictions issued by NMC are a unique product. Started in the early 1960's with methods developed at Air Resources Laboratory (ARL), they have undergone continuous development at NMC [38].

Other important research accomplishments which are already operational are methods for control of truncation error (higher order differences in the barotropic and three-level models) [39], use of ATS and Cb blow-off winds, and the initial operational methods for assimilation of asynoptic SIRS data [40].

Methods for NWP over the entire globe have been successfully developed at NMC, but are not operational yet. The approach used is to carry data on a grid of points separated by equal intervals of latitude and longitude. The regular latitude-longitude computational grid was a departure from conventional grids, in which points are everywhere separated by approximately equal distances. The justification for the regular grid, which is apparently inefficient in high latitudes where points are not well separated on latitude circles, lies in a theoretical analysis [41] developed at NMC showing excessive truncation errors in the more conventional grids in polar regions. The extra resolution in polar regions of the regular grid prevents such excessive truncation error.

Two models have been developed using the regular latitude-longitude grid, along with a finite-difference system [42] developed largely in a barotropic model. The first is a global model [43] with a 3.75° resolution in the horizontal and three layers in the vertical. It is addressed to the tropical problem and is global in order to take into account in a straightforward way the interactions between tropical and middle latitudes. It is almost ready for testing.

The second was designed as a successor to the NMC six-layer primitive equation model. It is hemispheric only, with its southern boundary at the equator. The reason for the model being cast in the regular latitude-longitude grid is to gain operational experience with global-type models. With such a model successfully in operation, NMC will be ready at any time to assume the full global responsibilities of a World Meteorological Center. It is also true, however, that in spite of its relative inefficiencies in very high latitudes, the regular latitude-longitude grid is more efficient overall from pole to equator than a regular square grid on a polar stereographic projection.

This second model with a regular latitude-longitude grid has a 2.5° resolution in the horizontal, and eight layers in the vertical. The vertical resolution is the same as in the six-layer model except for an extra layer in the stratosphere and an extra layer in the boundary layer. It will contain all the physical effects of the six-layer model. The high vertical resolution of the eight-layer model has reacted to the regular latitude-longitude grid in a way not well understood, with resulting low-grade instability problems. These problems have been solved through a combination of theory and experiment only during the last few weeks. It is now being completed and will soon be ready for testing.

In support of the global modeling efforts, a new system of global analysis [44] has been developed at NMC. It departs from the conventional grid-point-by-grid-point analysis structure, and is a direct analysis of amplitudes of a set of Hough functions in the horizontal, and natural orthogonal functions in the vertical. One advantage of this approach is that Hough functions are especially suitable for analysis of a mix of observations of wind and pressure over the globe. This is an operationally pertinent feature of the new system, since observations are, and will continue to be, of winds in low latitudes, and principally of pressures in high latitudes.

Following the Canadians, Kwizak and Robert [45], a semi-implicit difference system has been developed [46] [47]. A by-product of this research was the discovery that simple time-averages of pressure-force terms allows a doubling of the time step [48], and a consequent reduction of 50% in computer requirements for models. The time-averaging device is now ready for implementation in the six-layer model. The semi-implicit system promises another 50% reduction, but is more complicated to apply in the NMC six-layer model because of its type of vertical resolution. A new, highly resolved model is being designed to further test it.

Development of a fine-mesh planetary boundary-layer model (PBL) is well under way. The original model was developed for the Air Weather Service (USAF) by Gerrity [49] while he was at Travelers Corporation and has since been in operation at the Global Weather Central. The development of the LFM at NMC presents the opportunity of running PBL at NMC. It is a passive model, in the sense that it is driven by a fine-mesh prediction model. It has promise particularly in the air pollution and severe local storms areas.

Work is also being done in the area of stochastic-dynamical models [50]. This is an investment in the long-term future, since much more powerful computers will be required for feasibility. NWP will probably ultimately take this form, which provides not only deterministic predictions, but also information on probability of occurrence. Theory in this area is related to predictability theory.

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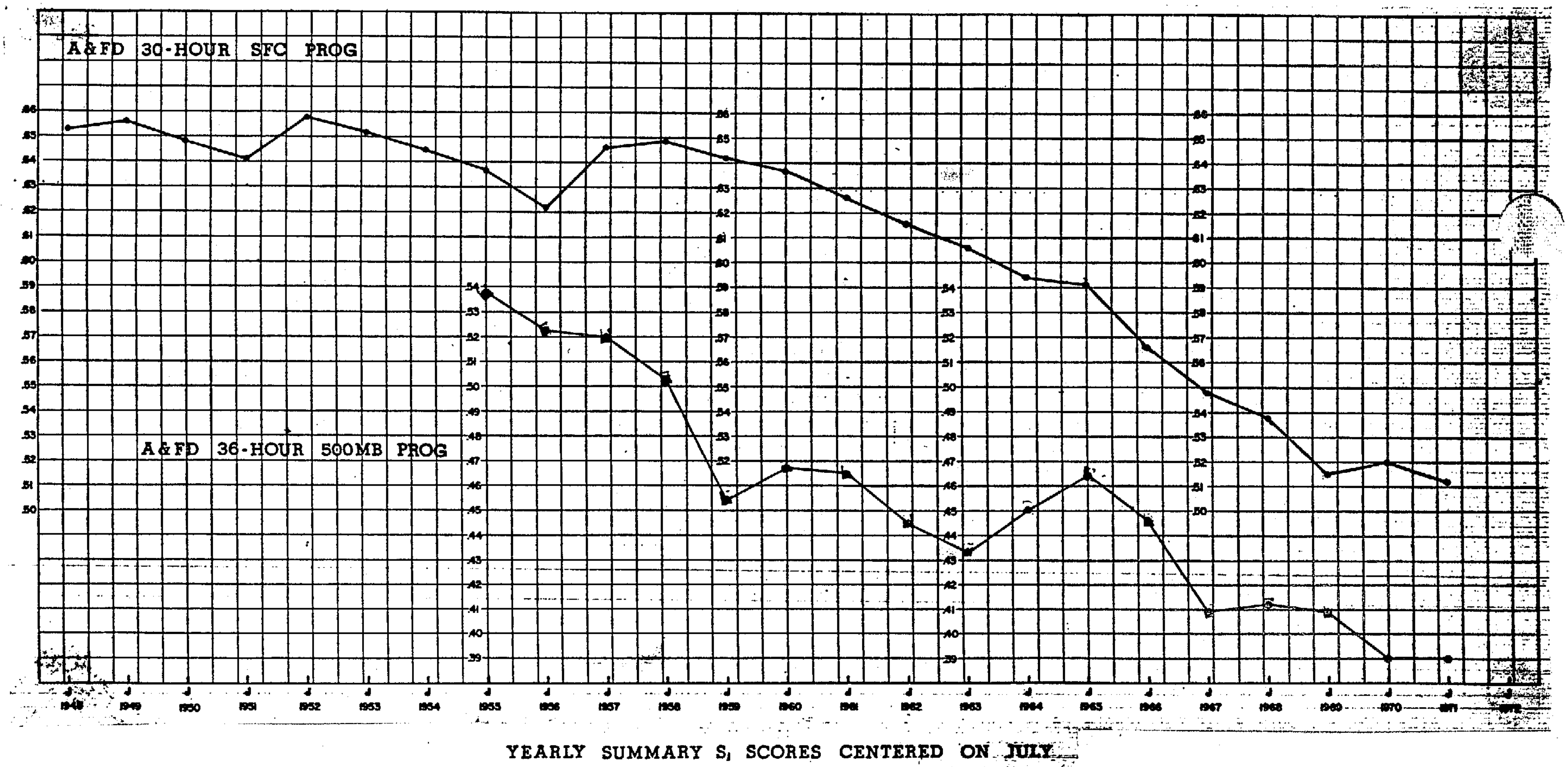

Figure 1. - Annual average S1 scores [51] for 30 hr sea level (upper curve) and 36 hr 500 mb (lower curve) forecasts. The S1 score is roughly a measure of normalized RMS vector error of pressure gradient. The area of verification for both levels covers North America. The two curves are plotted on the different scales shown. The scale for sea level is the one labelled from .50 to .66, the scale for 500 mb from .39 to .54. To calibrate the scores in terms of practical skill, a sea-level forecast with a score of .30 is virtually perfect, one with a score of .80 is worthless. For 500 mb, .20 represents a virtually perfect forecast, .70 worthless.